LANDFORMS: THEIR ROLE IN POLLUTION

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The term 'landform' has been used in the literature in a restrictive sense, in specific reference to surface features, as well as in a context so broad as to infer all of the attributes of "land". The context in which it is to be used, in the discussion to follow, is one of surface form and the associated lithology and structure of that form.

Many substances commonly referred to as pollutants are only so when they occur in undesired quantities in undesired locations. Generally, when in the "right" amount and in the "right" place they are not so considered. Consequently, it is often a matter of transmission from one location to another which changes a material from a fertilizer, manure pile, pesticide, fungicide or insecticide to a pollutant. It is in this transmission process that landforms are of relevance, for it is the shape and composition of the land surface which provides the impetus for and the resistance to transmission.

Relevant Pollutants

Before proceeding with the topic at hand, the transmission of potential pollutants, a few remarks pertaining to the nature and origin of these materials may be advisable. It is not the purpose here to consider the probability of these materials becoming pollutants but only to present some which have been mentioned in this vain and to consider them as potential pollutants. It is for experts of other fields to judge whether they are real or otherwise.

Fertilizers are frequently mentioned as sources of pollution. This is possible to solution by leaching, solution by run-off, and sediments carried by run-off (Cassell et al., 1971; Wagner and Dodds, 1971; Zubriski et al., 1971). The two major nutrient elements applied to Saskatchewan soils, nitrogen and phosphorous, have quite different potentials for transmission. Nitrogen, in the nitrate form, is susceptible to leaching in solution particularly in a wet year, under irrigation, in permeable soils, and under an absence of active and deep-rooted crops (i.e. summerfallow). Phosphorous, on the other hand, is unlikely to move in solution by leaching except perhaps in coarse textured soils. Both nitrogen and phosphorous are likely to be removed in solution or with soil particles suspended in run-off waters. Slope, infiltration rate and the erodibility of surficial deposits are relevant landform parameters in such transmissions. To the list of commercial fertilizers should be added pesticides, insecticides, animal and human wastes and many other materials which, through transmission in their original or some altered form, are apt to produce harmful effects to the environment of their new location (Gillham and Webber, 1970; Hedlin, 1971).

Surface Phenomena

From the foregoing, it is apparent that the nature of the landform is potentially a pollution-forming factor in that it may have a bearing on the transfer of materials, on or near the surface, through run-off, erosion, and leaching. The kind and extent of these transfers is highly dependent on landform factors such as slope, permeability, erodibility, drainage maturity, and regional physiography.

The shape and gradient of a slope or segment of a slope, along with the characteristics of upslope segments are important parameters related to run-off and erosion. Run-off and erosion are most prominent on the convex slope position with the accumulation of these materials occurring in the concave portion of the slope profile. A rectilinear slope, often occurring between these two segments, likely represents a condition of approximate balance between erosion and deposition (Small, 1970). While there is a well documented and direct relationship between the gradient of a slope and run-off and erosion, a factor which is often neglected is that soil losses from irregular slopes generally depend on the steepness of a short section of the slope immediately above the point of measurement (Young and Mutchler, 1969).

Texture and related permeability of the surficial deposits have a pronounced effect on infiltration, run-off, and erosion. Consequently, sandy and gravelly glacial-fluvial and lacustrine deposits tend to have higher infiltration and permeability rates and consequently are less subject to water erosion than glacial till and finer textured lacustrine deposits. Potential transfers in the coarse textured deposits would tend to be vertical, with the possible exception of snow-melt run-off, whereas in the finer textured deposits both horizontal transfers as erosion and run-off, as well as vertical transfers through leaching may be envisaged.

Texture as it relates to clay content and absorption of materials on the colloidal clay complex must also be considered. Surficial deposits high in clay tend to restrict vertical transfers of materials by absorption processes whereas deposits low in clay lack such a capacity to restrict movement of soluble materials through surface absorption.

The drainage maturity has a marked effect on transfer of materials in an area. Some land areas are characterized by the development of a network of gullies and streams leading to major streams, rivers or lakes. These areas, referred to as "open landform systems" (Ruhe and Walker, 1968) provide the opportunity for surface removal of materials from a local area through the drainage network.

Erosion and run-off from open landform systems is very obvious in that distinct and permanent gullies and streams provide the evidence. The formation of these drainage systems does not necessarily imply that total sediment transfers are any greater than in closed systems, to be discussed later. In addition, the presence of the drainage-ways does not necessarily suggest that the total area affected by sediment losses is greater than in closed systems. It is a distinct possibility, depending upon the drainage density, that surface transfers and surface area affected in an open system may indeed be of a lower magnitude than in closed systems.

It is a distinct possibility that in an open landform system many pollutants can be expected to be removed from the immediate area. The extent of their removal would appear to largely depend on the drainage density and the nearness of the source of the potential pollutant to a drainage-way.

Saskatchewan landforms more commonly reflect a "closed landform system" where drainage maturity has not developed and the landform consists of a series of undrained depressions. In such areas, run-off and erosion are common especially on rolling land of medium or fine textures. The transferred material collects at the base of steep slopes and in local basins or sloughs. In many landforms of this type a large portion of the total surface area is affected as erosion in these areas is frequently of the sheet type. Consequently, very shallow but extensive removal of materials can be expected. As a result, the potential for concentration of pollutants or potential pollutants in a local depressional area is quite high.

The regional physiography of an area considers such features as total relief, drainage maturity, and basin character. Is it mountainous, upland, midland, or lowland? Is there a well or immaturely developed drainage system? Does the drainage extend beyond the region in question or does it remain within the region? In Saskatchewan, we should be particularly careful to distinguish between some of the largest internal drainage basins on the North American continent (the Old Wives Lake Basin, Snipe Lake Basin, and the Quill Lake Basin) from externally drained plains such as those leading into the Missouri, Nelson, and Churchill River systems (Fig. 1). The inference is obvious. If there are pollutants or potential pollutants in Saskatchewan drainage waters the resting place and consequently the environment subject to potential pollution is highly dependent on the regional physiography.

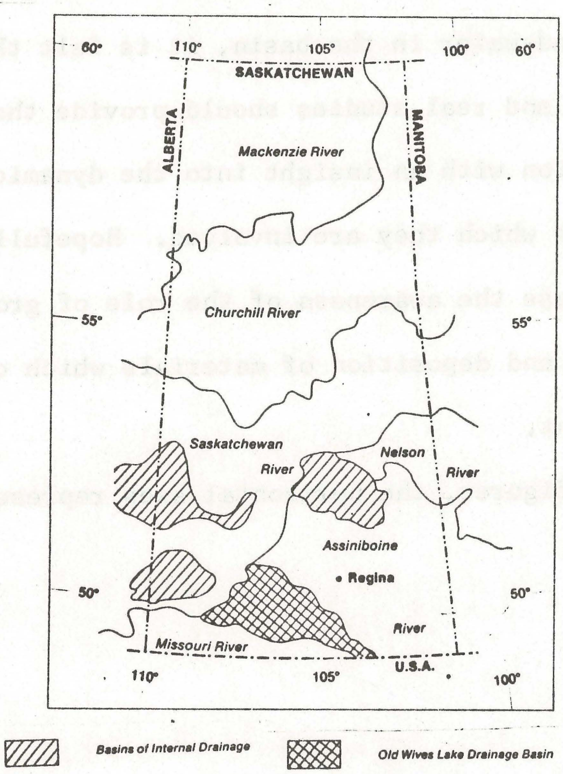

Figure 1. Location of internal drainage basins and external river drainage systems in Saskatchewan (Freeze, 1969).

Sub-surface Transfers

Sub-surface transfers refers to the movement of materials in association with what are commonly referred to as ground-water flow systems. Notwithstanding the fact there are rather severe knowledge gaps pertaining to water flow from the atmosphere, through the unsaturated soil zone to the saturated ground-water zone, it is generally accepted that the direction and rate of ground-water flow is frequently influenced by landform - the shape, composition, and structure of surface forms. It may be stated as a corollary that an acknowledgement, if not a complete understanding of both local and regional landforms can serve as a basis of appreciation of ground-water flow patterns and consequently may serve to indicate the location and rate of accumulation of pollutants.

It is the intention to examine a series of theoretical ground-water flow systems. The role or influence of landform in these studies will be stressed. This will be followed by the presentation of several case studies in the Old Wives Lake drainage basin in southern Saskatchewan (Fig. 1). Although every drainage basin likely has its own particular features regulating the distribution of ground-water in the basin, it is felt that an examination of these theoretical and real studies should provide those concerned with environmental pollution with an insight into the dynamics of the geohydrological environment with which they are involved. Hopefully, the discussion to follow will increase the awareness of the role of ground-water in the transfer, accumulation and deposition of materials which could conceivably pollute a new environment.

In each of the theoretical figures, the horizontal axes represents the lateral extent of the drainage basin (S). Realistically 1S could be considered to be 1, 5 or 10's of miles but perhaps most commonly about 5 miles. On the vertical axes is the total relief of the water-table or the difference in head or elevation of the water-table at one end of the basin as compared to the other (OS vs 1S). Also involved is the depth of the flow system. This is the vertical distance between the top of the water-table and some impervious layer at depth. In all of the illustrations the units on the horizontal and vertical axes are kept the same, that is, there is no vertical exaggeration. If, for instance, you assign 20,000 feet or approximately 4 miles to the lateral extent "S", then if the Depth/S is 0.1 the depth is 2,000 feet. If the Total Relief/S is 0.01, the water-table head is 200 feet along the 20,000 foot slope.

The upper boundary in these illustrations depicts the water-table boundary. In that it is generally considered that the water-table boundary largely reflects the topography of the surface, for the purpose of the discussion to follow the two may be considered to parallel each other. It may also be noted that the dotted lines on all the illustrations represent equipotential lines and the arrows indicate the direction of ground-water flow. In Fig. 2, the Relief/S is 0.0167 or about 2%. From this it is apparent that a gentle, constant regional water-table slope over a homogeneous medium results in a flow which is essentially horizontal. Recharge is concentrated at the upstream end of the recharge area, discharge at the downstream end of the discharge area. In this simple case, the "mid-line" is at the centre point of the slope. There is only one recharge area and one discharge area.

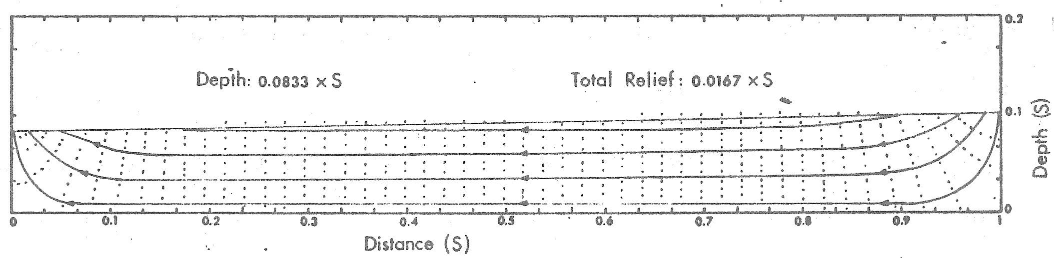

Figure 2. Ground-water distribution associated with a gentle, constant, regional slope (Freeze, 1969).

If the spacing between equipotential contours is x feet, then an equipotential line must meet the water-table at every point along its length which represents an increase in elevation of x feet. Steep water-table slopes therefore result in many equipotential lines and high gradients near the water-table. Shallow slopes are conducive to low gradients and near horizontal flow. Flat slopes represent equipotential lines themselves and result in very low upward or downward gradients.

The second theoretical situation to be considered involves a narrow flat valley with a steep valley flank and constant regional slope extending from valley edge to topographic high. The ground-water flow pattern and water-table configuration associated with such a landform sequence is presented in Fig. 3. In this case, the Relief/S is unchanged from that of 0.0167 presented in the previous theoretical consideration. The Depth/S also remains the same at 0.083. The existence of a major valley concentrates the discharge in the valley. The hinge line occurs midway up the steep valley flank. Two zones of concentration of recharge occur; one at the upstream end of the recharge area and the other in the recharge portion of the steep valley flank and extending just above the break in slope.

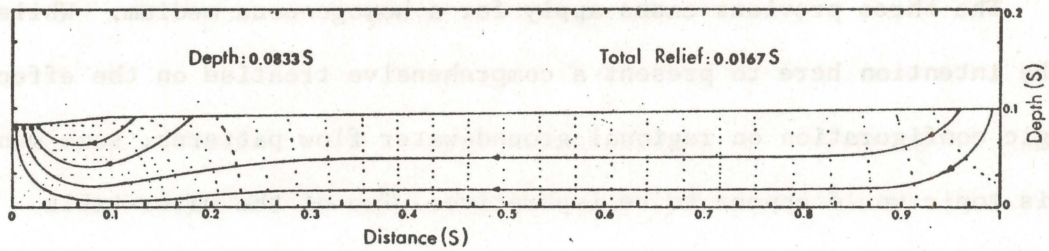

Figure 3. Ground-water distribution associated with a narrow flat valley with steep valley flank and constant regional slope extending from the valley edge to a topograhic high (Freeze, 1969).

The third theoretical case to be examined (Fig. 4) illustrates a broad flat valley with a water-table extending from the valley edge to a topographic high. This topographic high, unlike those in the previous cases, consists of a series of highs and lows superimposed on a regional slope. The existence of a hummocky water-table configuration results in numerous sub-basins within the major ground-water basin. Water which enters the flow system in a given recharge area may be discharged in the nearest topographic low, or may be transmitted to a distant minor topographic low or to the regional discharge area in the major valley bottom. In landforms producing water-table configurations such as this, the larger the depth/lateral extent ratio the larger the proportion of the recharge that enters the regional flow system. That is, the individual hummocks exert a smaller influence on the total flow pattern.

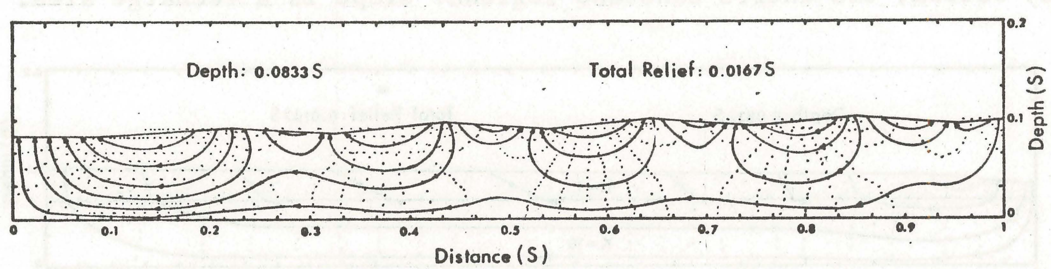

Figure 4. Ground-water flow pattern associated with a broad flat valley containing a water-table, extending from the valley edge to a topographic high consisting of a series of highs and lows superimposed on a regional slope (Freeze, 1969).

The three previous cases apply for a homogeneous medium. While it is not the intention here to present a comprehensive treatise on the effect of geologic configuration on regional ground-water flow patterns, some mention of this topic would appear to be imperative. Two of the water-table configurations presented for a homogeneous medium will be repeated with sediments representing a wide range of permeabilities.

The geologic configuration can generally be considered to affect the distribution of recharge and discharge areas as well as control the depth and lateral extent of the ground-water basins. In the first of the systems depicting a non-homogeneous geologic condition (Fig. 5) a narrow flat valley with a steep valley flank and a constant regional slope which extends from the valley edge to a topographic high is considered. In addition, this system contains a basal aquifer with a permeability 10 times greater than that of the overlying layer. The result is essentially horizontal flow through the aquifer. It is recharged through the low permeability layer above. A vertical component to the flow is thus introduced in the upper layer, one which did not exist in the homogeneous case. The downstream increase in the gradient in the aquifer should also be noted. The increase in gradient makes it possible for the aquifer to accept an increasing number of flow lines from the upper layer. The discharge is concentrated in the valley bottom; the entire constant regional slope is a recharge area.

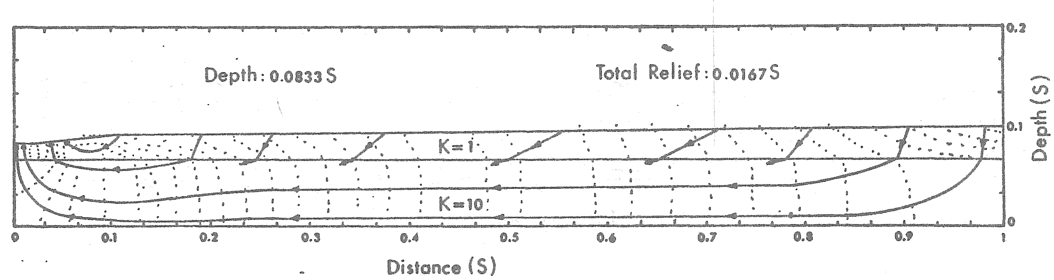

Figure 5. Ground-water flow system associated with a narrow flat valley with a steep valley flank and constant regional slope extending from the valley edge to topographic high and containing a basal aquifer of greater permeability than the overlying layer (Freeze, 1969).

As the permeability of the basal aquifer is increased in relation to the overlying sediment, the vertical upward or downward flow through the overlying low permeability layer becomes more pronounced. In addition, even though the horizontal gradient in the aquifer decreases the quantity of flow increases. Thirdly, the hinge line moves upslope, creating larger discharge areas. The next theoretical flow system to be considered is associated with a narrow flat valley containing a steep valley flank and associated with a constant regional slope which extends from the valley edge to the topographic high. A basal aquifer with a permeability 10 times less than that of the overlying layer is associated with this landform sequence. The ground-water flow system associated with such a landform is illustrated in Fig. 6. It should be noted that the flow pattern resulting from such a geologic system is almost identical to that of the homogeneous case.

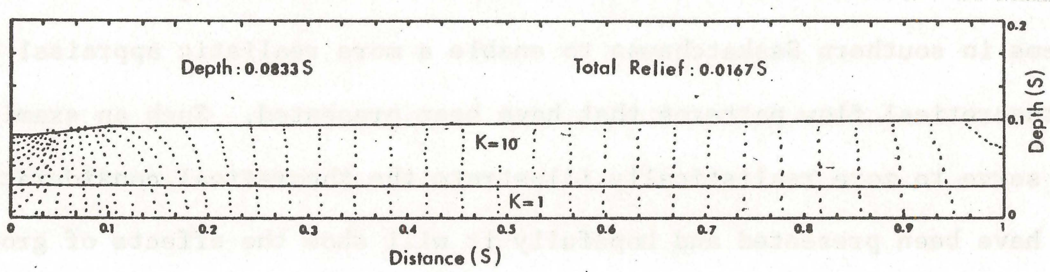

Figure 6. Ground-water distribution associated with a narrow flat valley with a steep valley flank and constant regional slope extending from the valley edge to topographic high and containing a basal aquifer of lesser permeability than the overlying layer (Freeze, 196

In summary, the presentation of these theoretical cases should serve to illustrate that there is a very definite relationship between the landform or a series of landforms in an area and the water-table configuration. From this it follows that given a certain water-table configuration it is possible to predict the nature and quantity of ground-water flow which may be expected in an area if the relative permeabilities of the materials are known. The application of this to pollution would appear to lie in the fact that pollutants, or potential pollutants, which may be leached from surface soils into the ground-water system will become part of that ground-water system, move with it, and may re-occur at the surface at some point at considerable distance from the original point of entry into the ground-water flow system. There is another factor to be considered here which I will only mention briefly and that is one of time. Depending upon the lateral extent, the water-table configuration, and the geologic composition of the drainage basin, the time which may elapse from when the material entered the ground-water system until it may be discharged from that same system may possibly be appropriately measured in decades. Once again I think the significance of this is obvious when we consider the potential of pollution to the environment.

It is the intention now to examine several actual ground-water flow systems in southern Saskatchewan to enable a more realistic appraisal of the theoretical flow patterns that have been presented. Such an examination will serve to more realistically illustrate the theoretical considerations that have been presented and hopefully it will show the effects of ground-water flow, or the potential effects of ground-water flow, in a real environment in Saskatchewan.

The first system to be studied is one extending from the Wood Mountain Upland near the United States border northeastward to the vicinity of Gravelbourg and extending in the direction of Old Wives Lake. The landforms, surficial and bedrock deposits of this area are illustrated in Fig. 7.

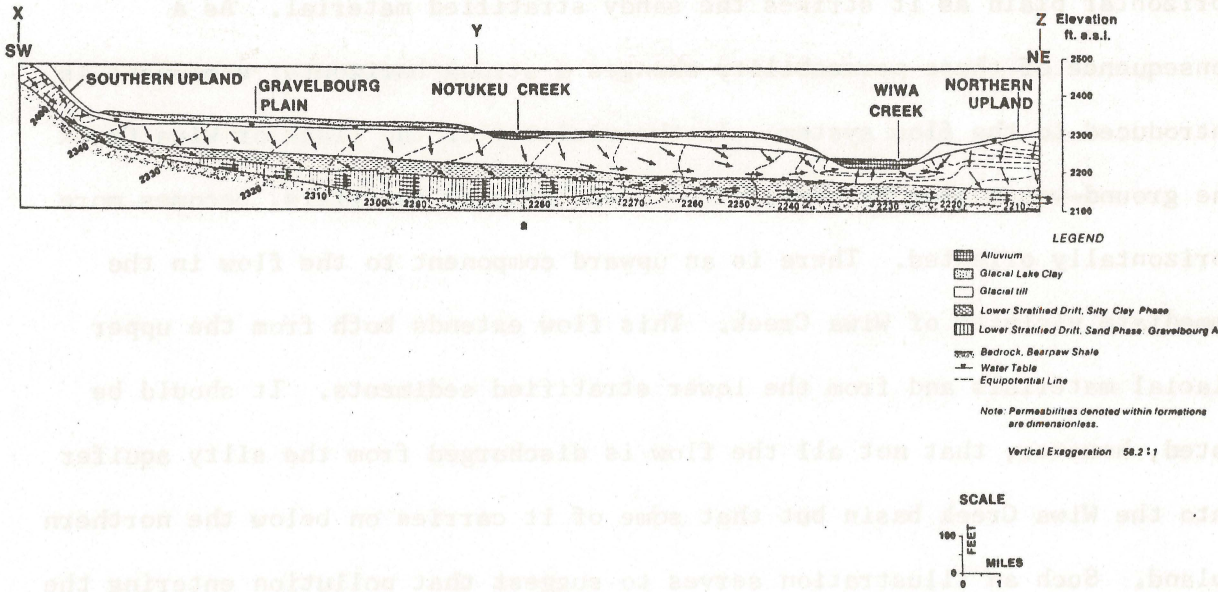

Figure 7. Ground-water flow pattern in the transect extending from the Wood Mountain Upland through Wiwa Creek toward Old Wives Lake, in Southern Saskatchewan (Freeze, 1969).

A thin layer of glacial lake clay occurs above a relatively thick glacial till deposit throughout most of this area. Underlying the glacial till are two units of stratified drift. The uppermost unit is silty but has a considerably higher permeability than the till and the lacustrine materials above it. The lowermost stratified unit is sandy and has a very much higher permeability than the silty stratified drift. The ground-water flow patterns associated with such a sequence of landforms and geological deposits are apparent in Fig. 7. In the vicinity of the southern upland, ground-water flow in the glacial materials is largely of a lateral nature moving out onto the plain below. In the vicinity of the Gravelbourg plain, the ground-water flow extends downward from the surface but is deflected as it enters the silty stratified drift and deflected even further into a horizontal plain as it strikes the sandy stratified material. As a consequence of these permeability changes a strong horizontal component is introduced to the flow system. In the vicinity of the flank of Wiwa Creek the ground-water flow pattern, even in the glacial materials, becomes more horizontally oriented. There is an upward component to the flow in the immediate vicinity of Wiwa Creek. This flow extends both from the upper glacial materials and from the lower stratified sediments. It should be noted, however, that not all the flow is discharged from the silty aquifer into the Wiwa Creek basin but that some of it carries on below the northern upland. Such an illustration serves to suggest that pollution entering the soil and extending to the ground-water system in the Wood Mountain Upland or along the Gravelbourg plain would tend to eventually be carried in a horizontal direction through the sandy and silty aquifers to be discharged in part in Wiwa Creek and also in more northern discharge areas.

The pattern of ground-water flow in an actual field situation in the Ormiston-Readlyn area east of Assiniboia has also been studied (Freeze, 1969). This transect extends southward from the Dirt Hills, consisting of a ridged and hummocky morainic landform with a closed drainage system, through a lower lying undulating glacial-fluvial outwash plain over two more morainic areas with a slight trough in between and ending in Willow Bunch Lake, near Readlyn.

A simplified sketch of the equipotential lines and ground-water flow lines is presented in Fig. 8 (Freeze, 1969). It should be noted that the glacial till is 50 to 100 feet thick and overlies Ravenscrag, Whitemud and

Eastend bedrock formations. The permeability of the bedrock materials, in particular the Eastend sandstone, is considerably higher than the overlying silty and clay bedrock and glacial materials. The ground-water flow patterns, as illustrated in Fig. 8, suggest the very strong recharge area occurs in the Dirt Hills. This joins the sandy aquifer and is likely to be discharged in the lower glacial-fluvial plain in the vicinity of Shoe Lake. A very similar recharge area to the one in the Dirt Hills occurs on each of the morainic uplands to the south. The sandy aquifer once again converts this vertical ground-water flow to one in a horizontal direction and extending in both directions from the highs so that ground-water may flow northward to Shoe Lake as well as southward to the Willow Bunch Lake from these morainic uplands. It should also be noted that the strong relief characteristic of the morainic areas and the presence of a sandy aquifer minimizes local ground-water flow systems in the morainic areas and particularly in the small, low or depressional area between the two southern morainic uplands. A strong upward movement of ground-water flow from the sandy aquifer is shown on the extreme left hand side of the illustration. Such a flow has undoubtedly led to the concentration of salts characteristic of these lakes. The implication toward pollution of such a sequence of landforms and geologic strata may be summarized by stating that with a strong relief characteristic of many of these areas very few local flow systems may be anticipated and consequently the major morainic areas such as the Dirt Hills can be considered essentially entirely recharge in nature. Lower areas, irregardless of the geologic materials present, are potentially discharge areas as is illustrated in Willow Bunch Lake and Shoe Lake. There is a definite upward component of ground-water in these Lakes and pollution materials can be expected to move with these ground-waters in their vicinity.

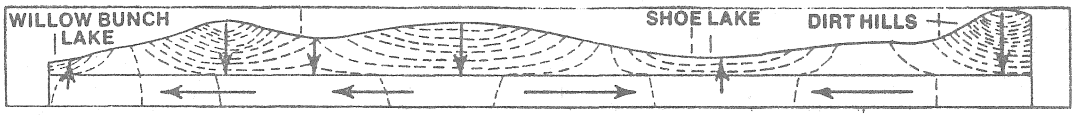

Figure 8. Ground-water flow pattern in the transect from the Dirt Hills to Willow Bunch Lake in Southern Saskatchewan (Freeze, 1969).

Conclusions

The nature and extent of environmental pollution is highly dependent on transmission processes for it is often through these processes that levels of substances that are harmful to an environment may accumulate. The conformation and composition of the land surface strongly influences the distribution of water on the surface; the "run-off" from this surface and the "run-in" entering the surface.

Open landform systems are conducive to the removal of materials from an immeidate area and collection occurring in an interior basin or an ocean. Closed systems generally result in local transfer with collection in small depressional areas.

Surface transfers are facilitated through landforms of a rolling or hilly nature and fine texture. Whereas gently sloping or level landforms, especially when associated with permeable surficial deposits low in clay are more conducive to vertical transfers.

Movement of materials within surficial deposits can be expected to be associated with groundwater flow. Water-table configuration, as it reflects surface configuration of a local and regional nature, has a marked effect on transfer of materials through the groundwater system. In addition, the composition of surficial and sub-surface layers have a pronounced effect on bulk flow systems.

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